Measurements of Atmospheric CO_2 Column in Cloudy Weather Conditions using An IM-CW Lidar at 1.57 Micron

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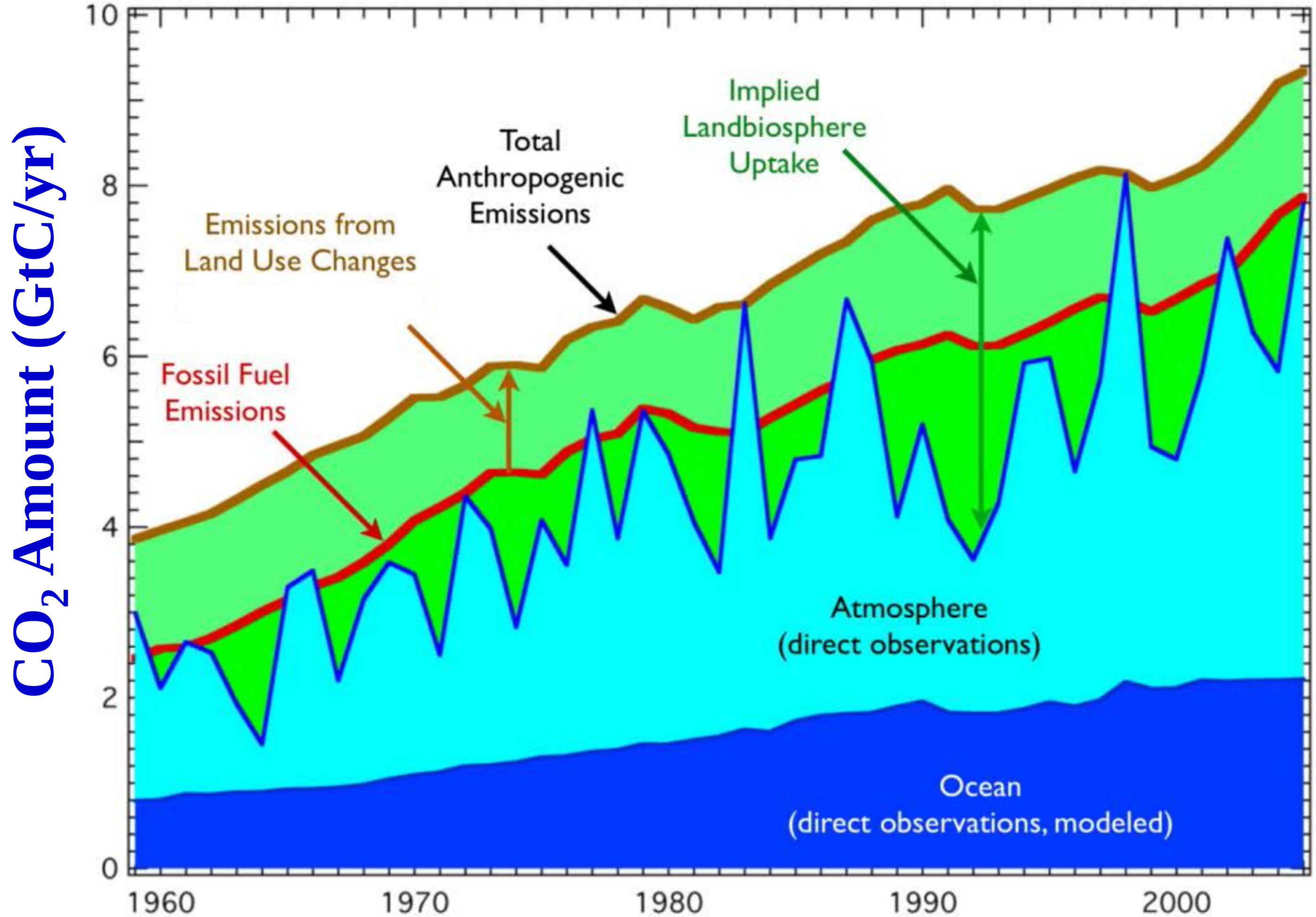
Outline

- **Introduction**
  - Carbon sciences and challenges
  - Lidar CO_2 measurement approach
  - Instrumentation and flight campaigns
- **Lidar Measurements**
  - In-situ observations for validation
  - Accuracy of CO_2 measurements
  - Precision of CO_2 measurements
  - Ranging measurements
  - CO_2 measurements through thin clouds
  - CO_2 column measurements to cloud tops
- **Summary**

Annual CO_2 Budget & Variation

Terrestrial sink: residual >>> large errors



Fossil Fuel: 9.1±0.5 ; Land Use: 0.9±0.7

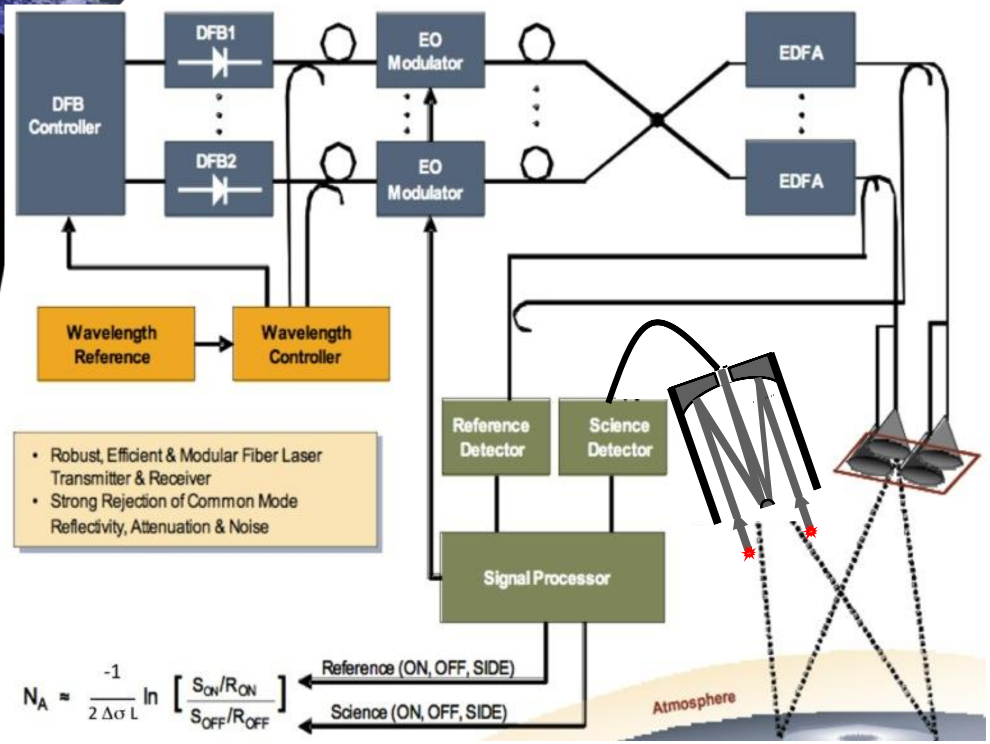
Land Sink: 2.6±1.0; Atmo: 5.0±0.2; Ocean: 2.4±0.5

Land plants and ocean uptake removes some of atmospheric CO_2

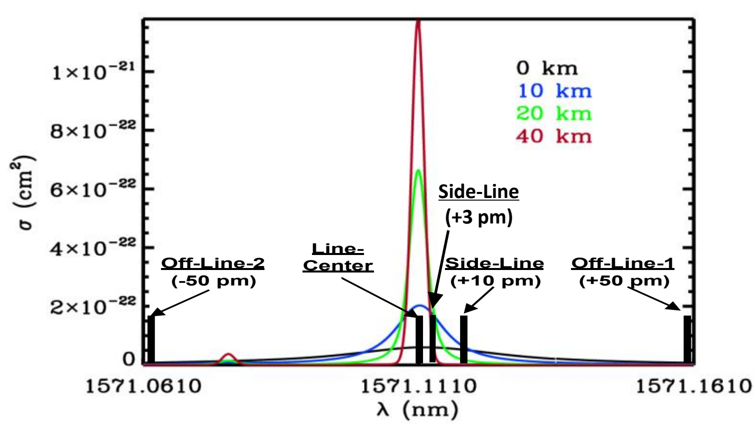
Atmosphere CO_2 budgets: large variations

Prediction of this trend and variability, especially in changing climate (?)

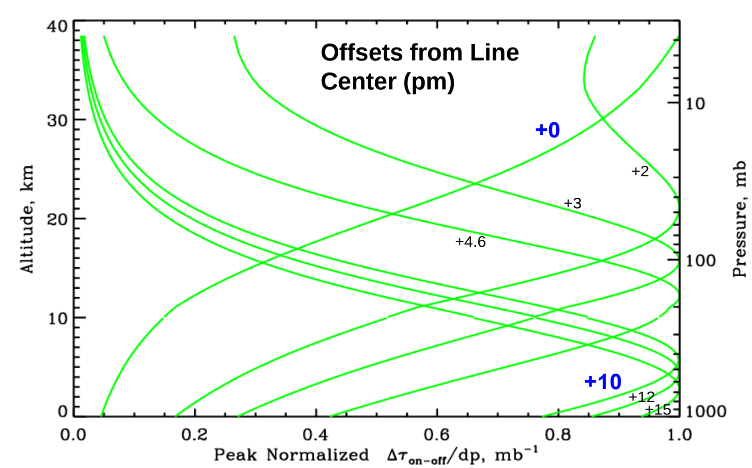
CO_2 Measurement Architecture IM-CW Laser Absorption Lidar



- Simultaneously transmits λ_{on} and λ_{off} reducing noise from the atmosphere and eliminating surface reflectance variations.
- Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 µm) number density measurements, combining them to derive XCO_2.



Weighting Functions



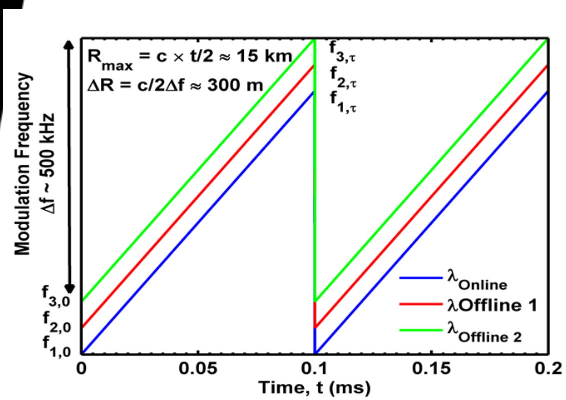
IM-CW Laser Absorption Lidar
1.57-µm CO_2 Measurement Technique

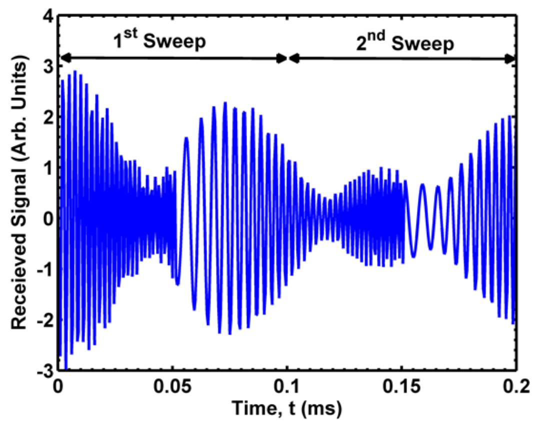
Multiple channel Intensity Modulations: orthogonal waveforms

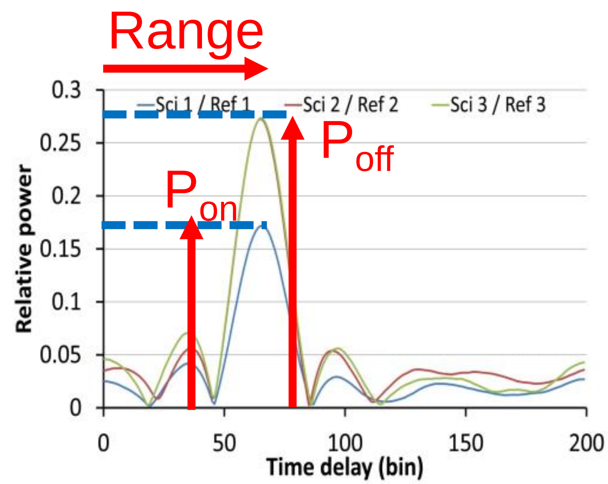
Simultaneously transmitted Intensity modulated range encoded waveforms

Simultaneously received Online and Offline IPDA returns

Measurement: Output of correlation between transmitted and received waveforms







Range encoded approach for detection and ranging is analogous to mature CW Radar and GPS measurement techniques

$$DAOD = \frac{1}{2} ln\left(\frac{P_{off} * E_{on}}{P_{on} * E_{off}}\right)$$

Airborne System Demonstration

ASCENDS CarbonHawk Experiment Simulator (ACES developed at LaRC with support from Harris)

Multifunctional Fiber Laser Lidar (MFLL) (developed by Harris in 2004 Harris and Langley since 2005)

advancing key technologies for spaceborne measurements of CO_2 column mixing ratio

Development & Demonstration

ASCENDS

21-25 May 2005, Ponca City, OK (DOE ARM)
5 Lear Flts: Land, Day & Night (D&N)

20-26 June 2006, Alpena, MI
6 Lear Flts: Land & Water (L&W), D&N

20-24 October 2006, Portsmouth, NH
4 Lear Flts: L&W, D&N

20-24 May 2007, Newport News, VA
8 Lear Flts: L&W, D&N

17-22 October 2007, Newport News, VA
9 Lear Flts: L&W, D&N, Clear & Cloudy

22 Sept. – 30 Oct. 2008, Newport News, VA
10 UC-12 Flts: L&W, D&N, Rural & Urban

10-16 July 2009, Newport News, VA
5 UC-12 Flts: L&W

31 July – 7 Aug. 2009, Ponca City, OK
5 UC-12 Flts: L&W, D&N

10-20 May 2010, Hampton, VA
6 UC-12 Flts: L&W, D&N

5-11 May 2011, Hampton, VA
5 UC-12 Flts: L&W, D&N, Clear and Cloudy

6-18 July 2010, Palmdale CA
6 DC-8 Flts: L&W, D

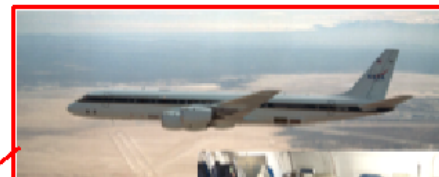
28 July – 11 Aug. 2011, Palmdale CA
8 DC-8 Flts: L&W, D

February 19 – March 9, 2013, Palmdale CA
7 DC-8 Flts: L&W, D&N

August 13 – September 3, 2014, Palmdale CA
5 DC-8 Flts: L&W, D


MFLL on Lear-25


MFLL on UC-12



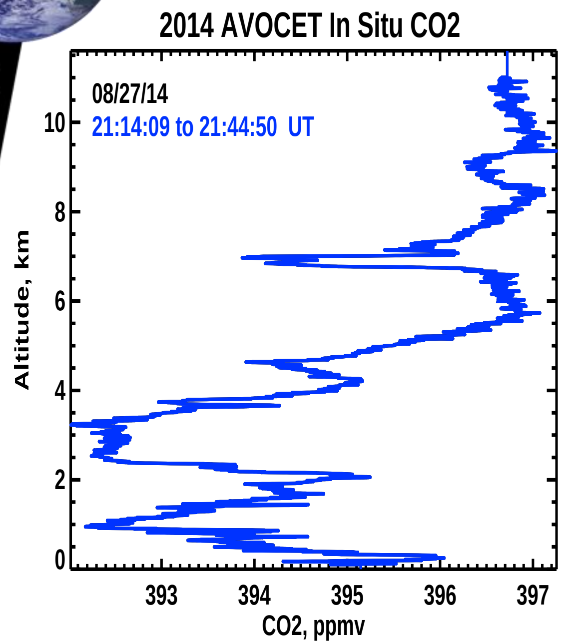

MFLL on DC-8

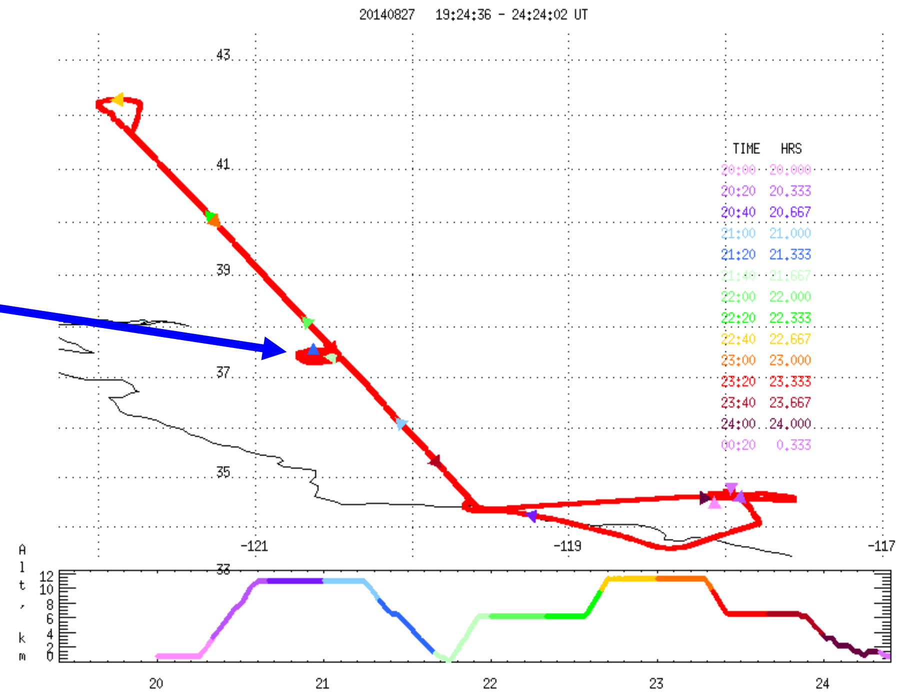
various lab, ground range, and flight tests

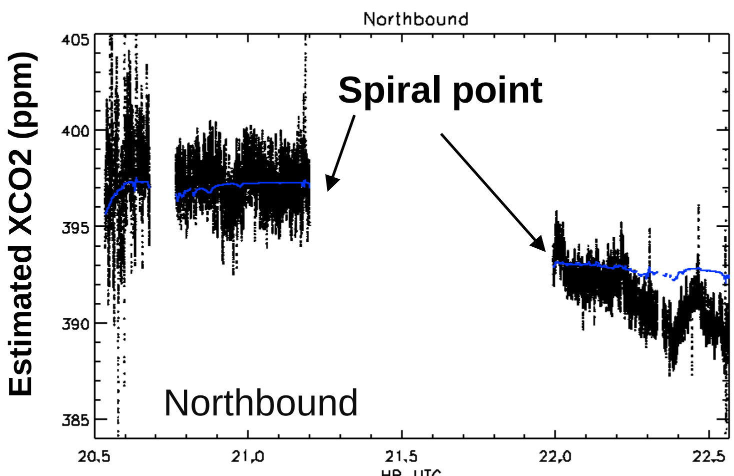
ranging capability enabled

total 14 MFLL flight campaigns since 2005, plus 1 ACES in Hampton, 2014

In Situ and Lidar Comparision
(MFLL OCO-2 Under Flight: 20140827)







Black curves: lidar measured XCO2

Blue curves: in-situ derived XCO2

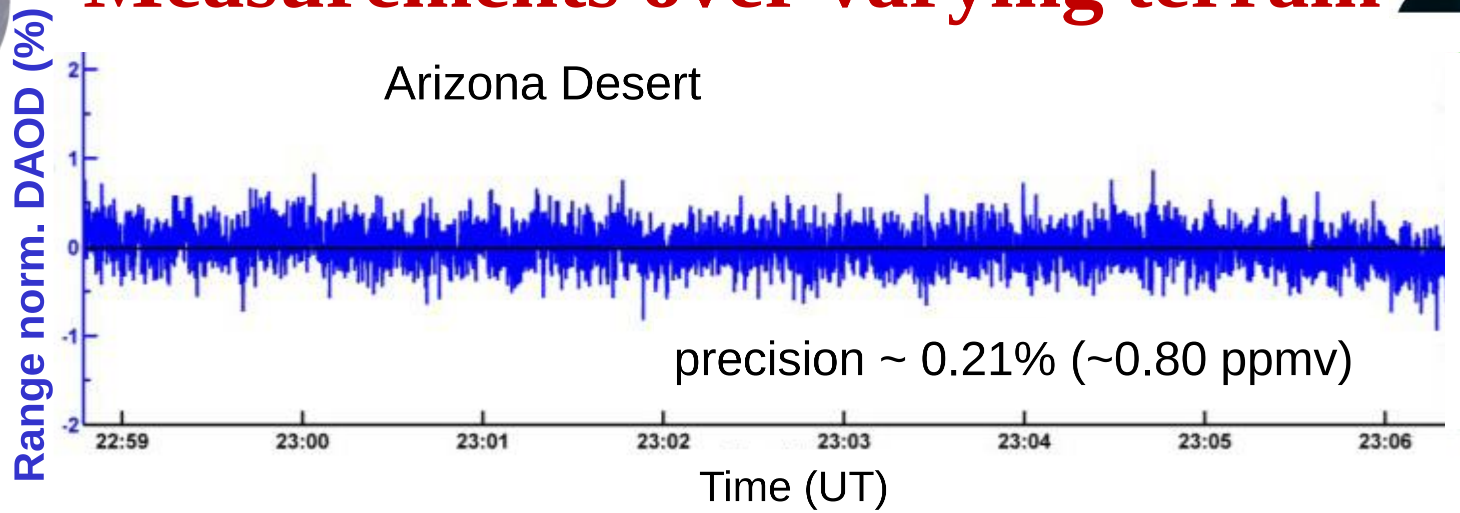
In-situ derived (or modeled) Value

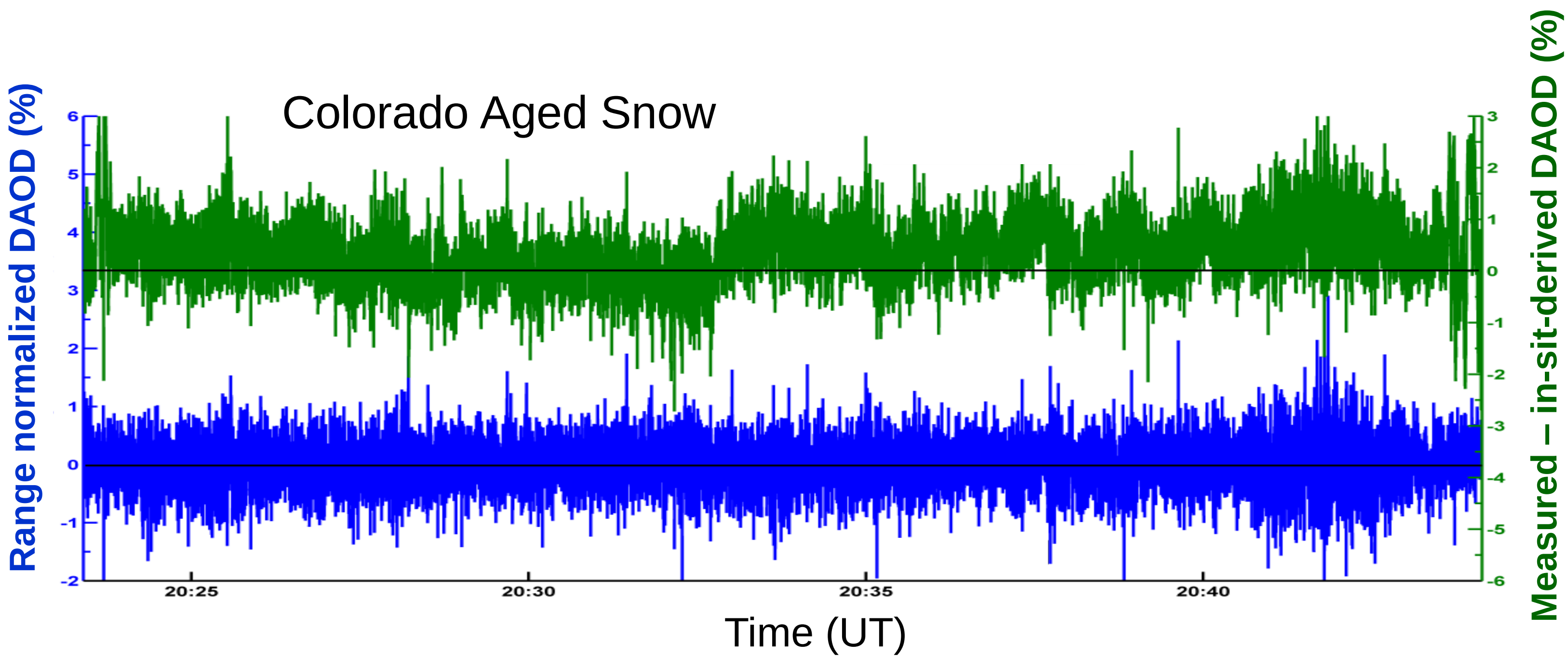
- In-situ from Spiral: XCO_2, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) XCO_2

difference (ppm): 0.18

2013 ASCENDS Campaign: Measurements over varying terrain

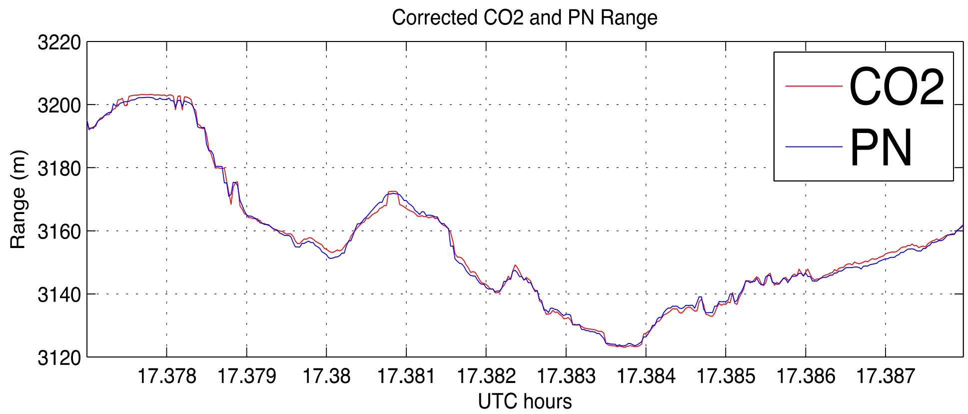
1-s average

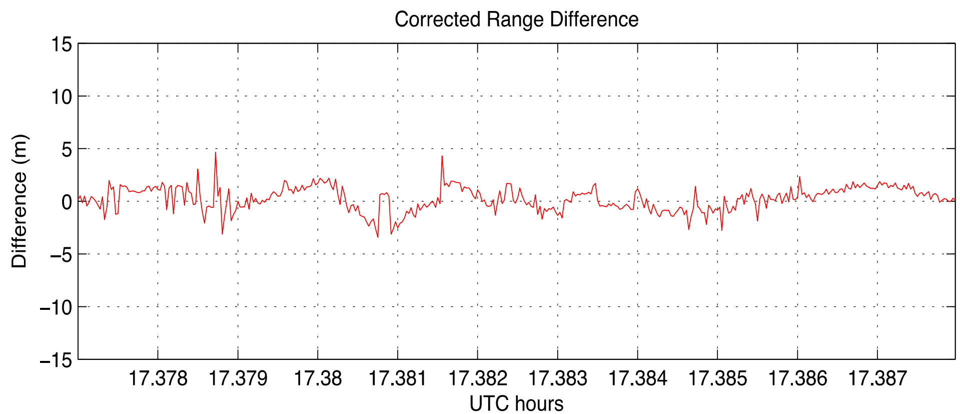




difference ~ 0.26% (~0.99 ppmv); Precision ~ 0.42% (~1.6 ppmv)

Comparison of Range Determination from PN Altimeter and Off-line CO_2 Signal

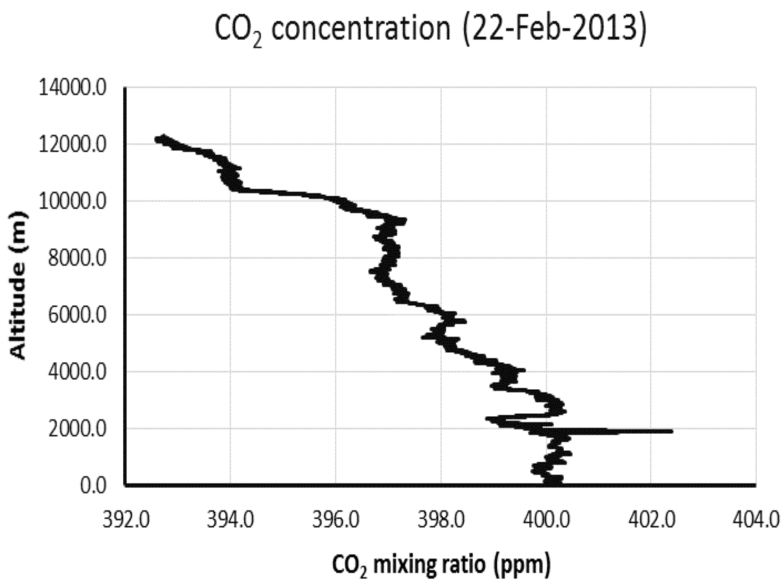


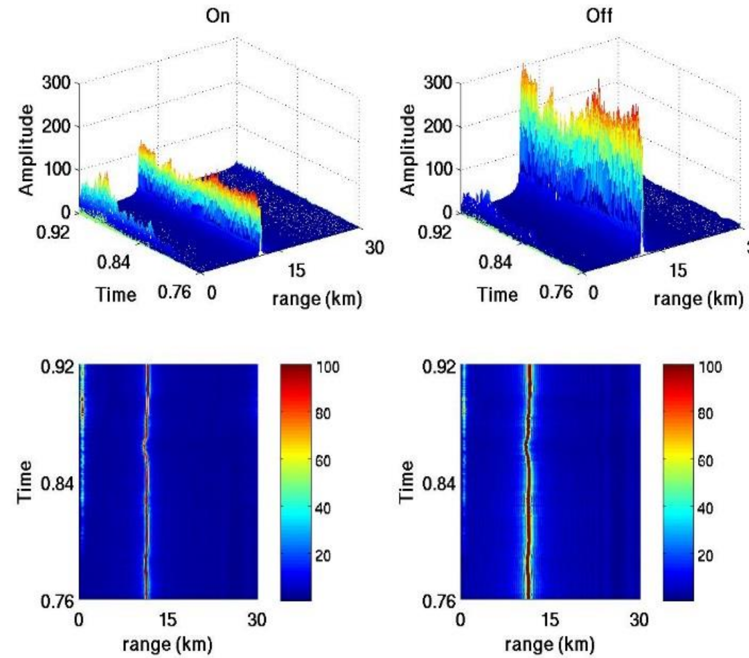


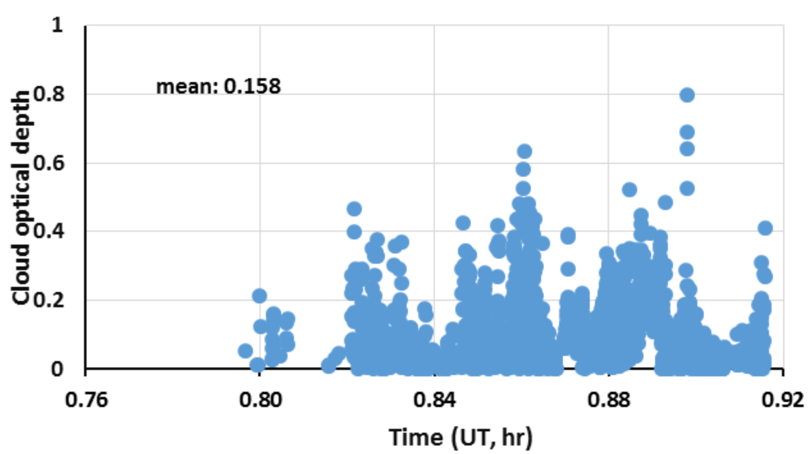
RMS errors < 3 m

Range estimates obtained from the off-line CO_2 return and time coincident returns from the onboard PN altimeter over the region of Four Corners, NM from the DC-8 flight on 7 August 2011.

CO_2 Column Measurements Through Thin Cirrus (22 Feb 2013)



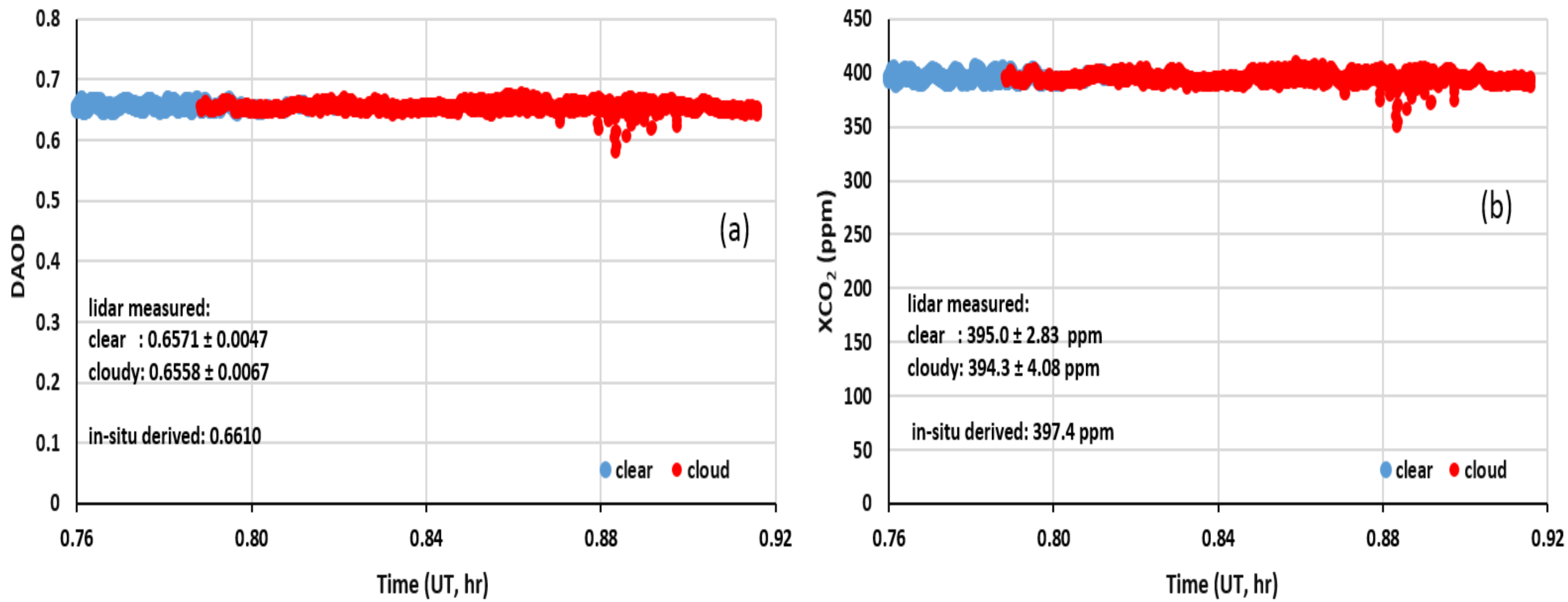




10 Hz data

Column CO_2 DAOD and Equivalent XCO_2 Measurements

consistent CO_2 column observations obtained for clear and cloudy conditions

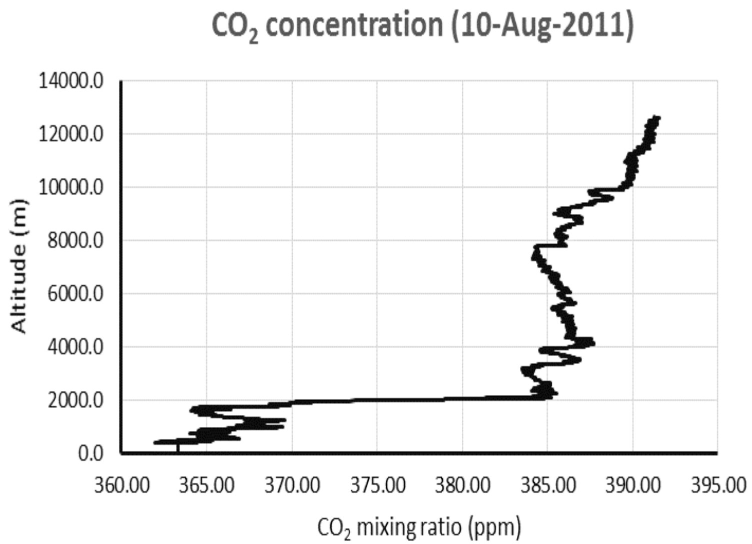


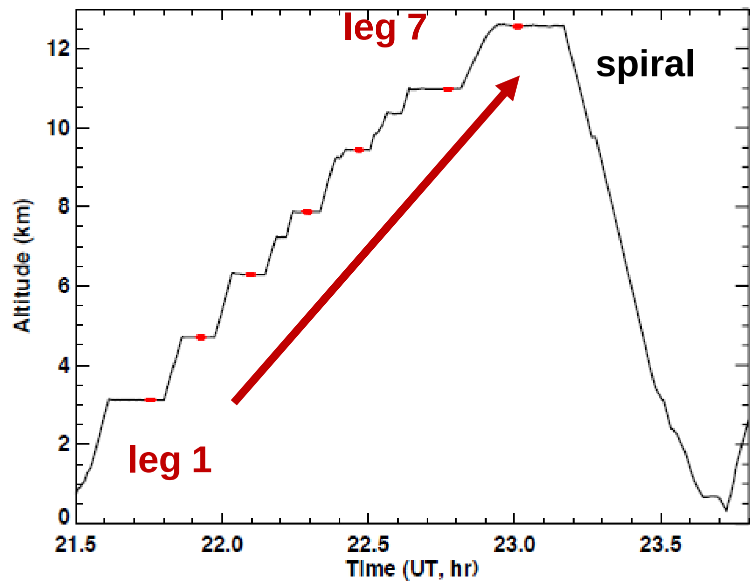
cloudy XCO2– clear XCO2 = –0.7 ppm

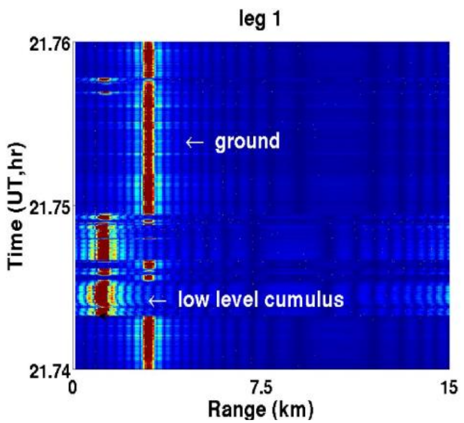
10 Hz data

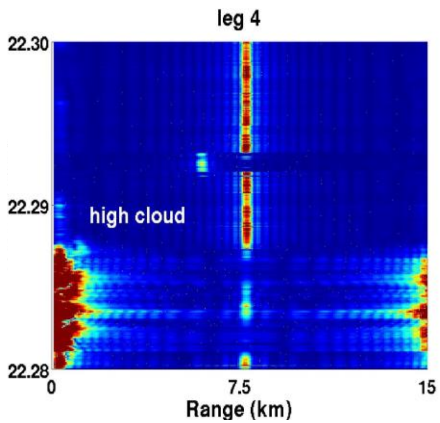
CO_2 Column Measurements over Thick Low Level Clouds

(10 Aug 2011)



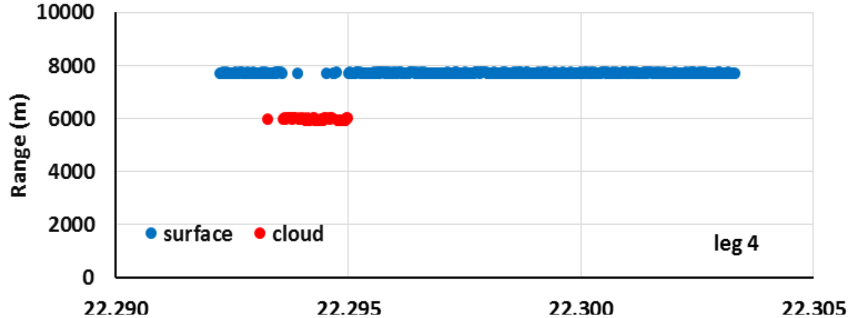


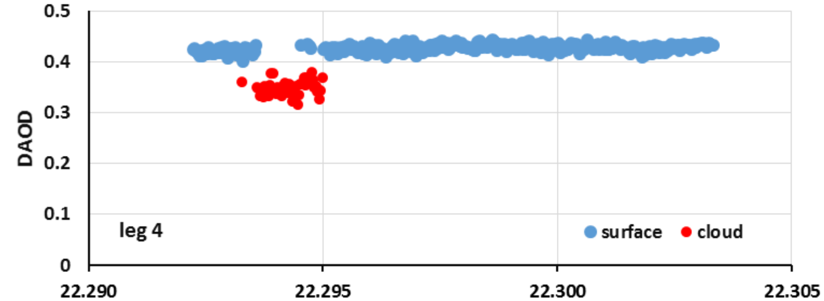


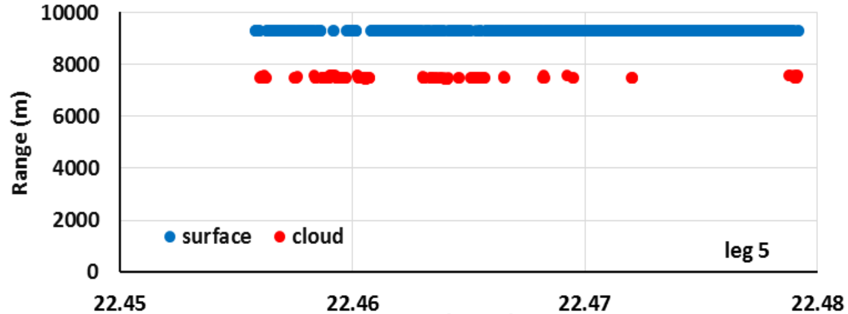


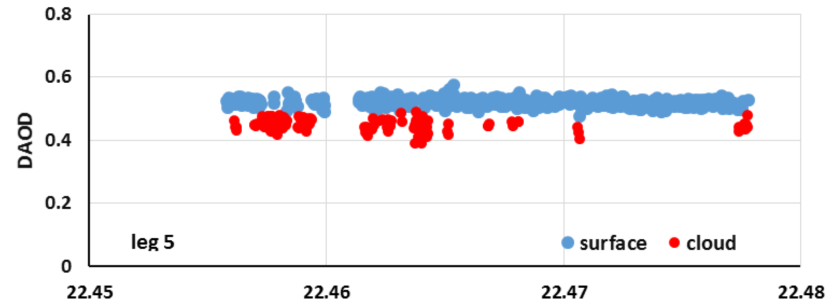
- Sufficient CO_2 absorption for DAOD measurements
- Strong enough signals to low level thick clouds
- Legs: 4, 5, 7

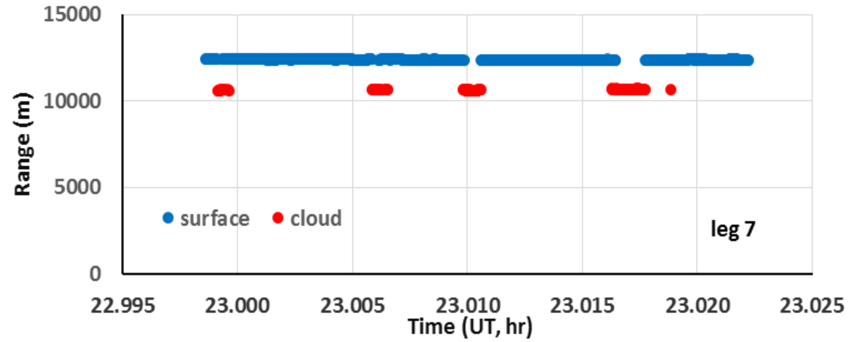
Range and Column CO_2 to Surface and Thick Cloud Tops

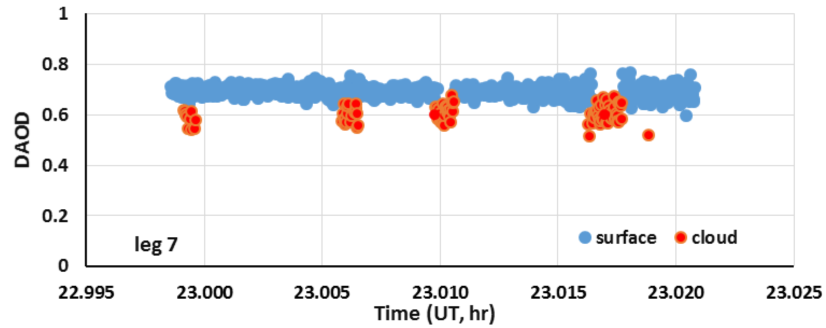












10 Hz data

Column CO_2 Measurements to Surface and Thick Cloud Tops

	Leg 4	Leg 5	Leg 7
lidar $DAOD_{surface}$	0.4271 ± 0.0056	0.5196 ± 0.0093	0.6902 ± 0.0155
lidar $DAOD_{cloud}$	0.3480 ± 0.0143	0.4368 ± 0.0243	0.6007 ± 0.0339
lidar $DAOD_{bndrylyr}$	0.0791 ± 0.0154	0.0828 ± 0.0260	0.0895 ± 0.0373
In-situ $DAOD_{surface}$	0.4243	0.5160	0.6939
In-situ $DAOD_{cloud}$	0.3417	0.4334	0.6075
In-situ $DAOD_{bndrylyr}$	0.0826	0.0826	0.0826
lidar $XCO2_{surface}$	383.2 ± 5.02	384.3 ± 6.88	381.6 ± 8.57
lidar $XCO2_{cloud}$	391.5 ± 16.09	387.7 ± 21.31	382.0 ± 21.56
In-situ $XCO2_{surface}$	380.8	381.7	383.8
In-situ $XCO2_{cloud}$	384. 6	384.9	386.4

10 Hz data

Summary

- **Global/regional atmospheric CO_2 observations require high accuracy and precision measurements owing to very small variations in atmospheric CO_2 mixing ratio.**
- **Laser absorption lidar at 1.57μm with ranging-encoded IM provides advanced capability in cloud/aerosol discriminations.**
- **IM-CW lidar has demonstrated the capabilities of precise CO_2 measurements through many airborne flight campaigns under variety of environment conditions, including CO_2 column measurements through thin cirrus clouds and to thick clouds. For low level clouds, boundary layer CO_2 measurements consistent with in-situ observations can be obtained.**
- **Analysis shows that current IM-CW lidar approach will meet space CO_2 observation requirements and provide precise CO_2 measurements for carbon transport, sink and source studies.**